What have we learned from Planck about technology, foregrounds, calibration and systematics?

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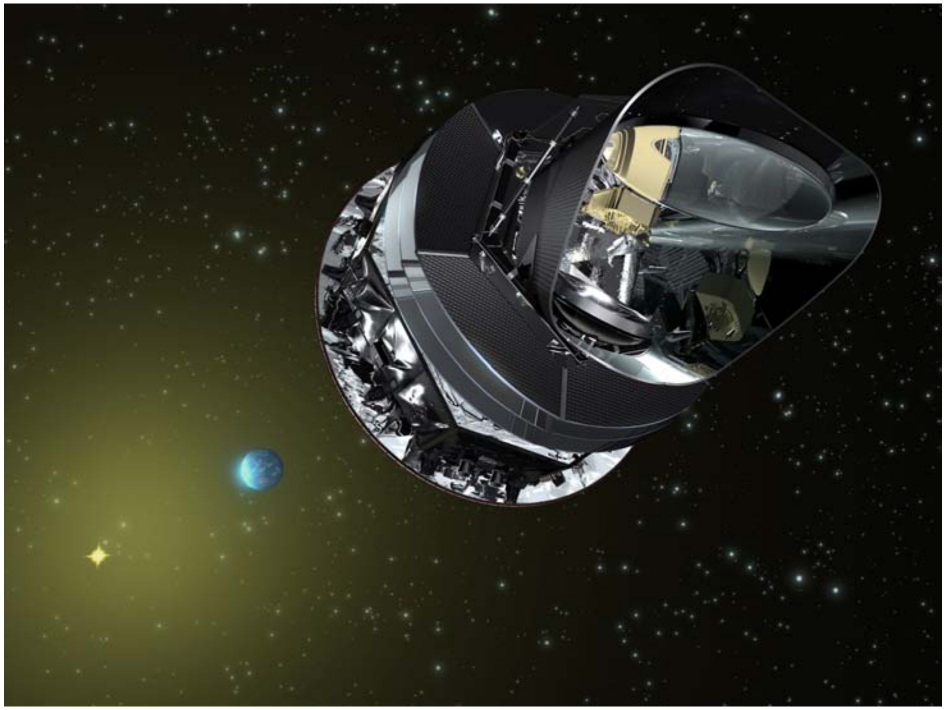
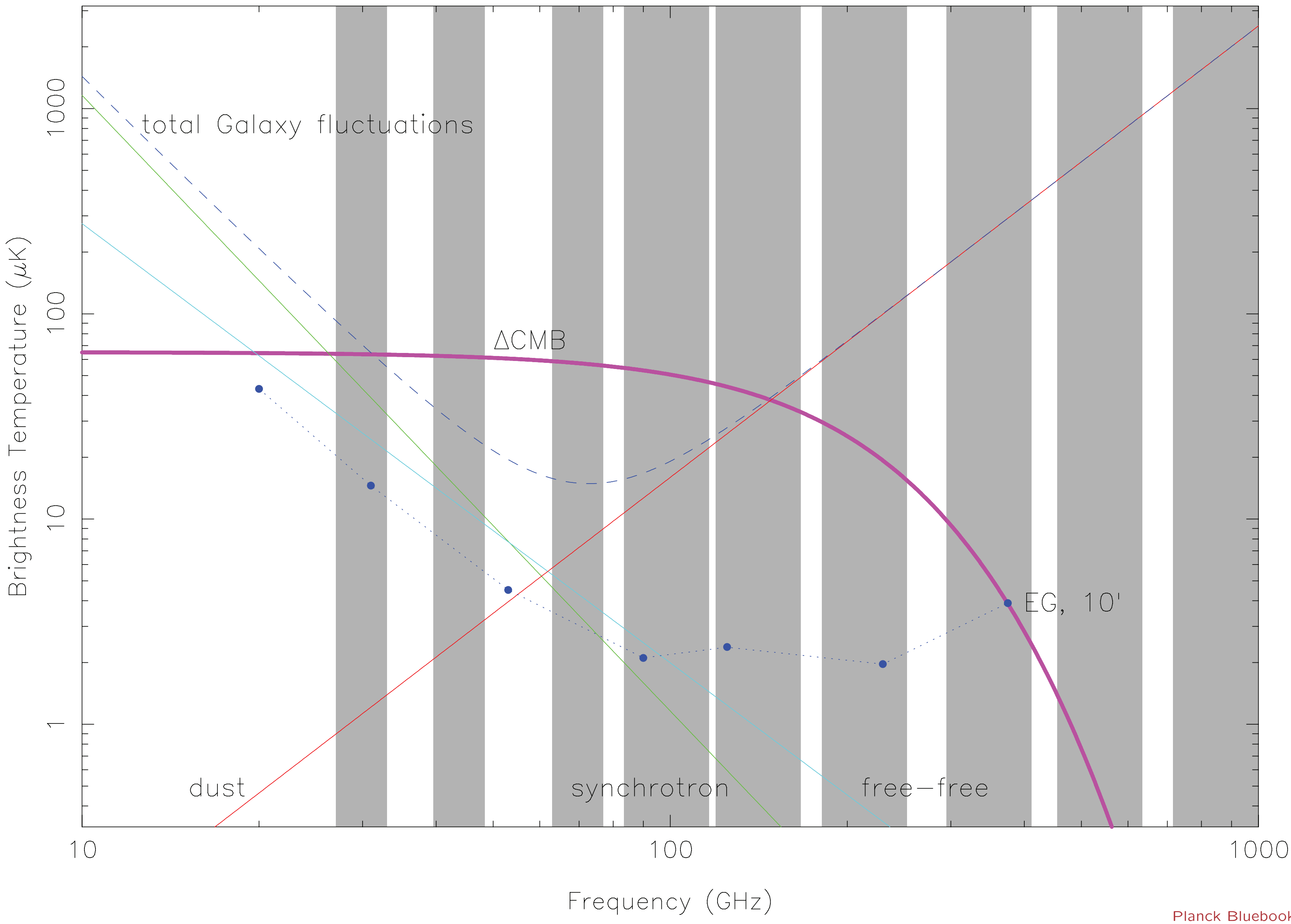
Planck

- Primary design goal was to measure temperature anisotropies of the CMB to fundamental limits down to 5′
  - Fly at L_2 with two instruments:
  - Low Frequency Instrument (LFI), with 20-K amplifiers at three frequencies
  - High Frequency Instrument (HFI), with 0.1-K bolometers at six frequencies



- Temperature measurement at nine frequencies
  - 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
- Polarization measurements at seven frequencies
  - 30, 44, 70, 100, 143, 217, 353 GHz

Planck Frequencies



Planck Bluebook

First Things First

- Planck has worked superbly, HFI, LFI, and the entire cryo system
  - One on-board "failure" in 36 months: the computer had to be rebooted on 14 January 2012.
  - Thermal design with agressive radiative cooling and active coolers is the wave of the future.
- Planck is delivering on its promised unprecedented combination of sensitivity, angular resolution, and frequency coverage

Data releases

- January 2011 — ERCSC and Planck Early Results, 26 papers on in-flight performance and astrophysics. A&A vol. 536

  Planck early results. II. The thermal performance of Planck

  Planck early results. III First assessment of the Low Frequency Instrumt in-flight performance

  Planck early results. IV. First assessment of the High Frequency Instrument in-flight performance

  Planck early results. V. The Low Frequency Instrument data processing

  Planck early results. VI. The High Frequency Instrument data processing

- 2011–2012 — Planck Intermediate Results, expect 25 more astrophysics papers
- Early 2013 — First data and cosmology results

  First 15.5 months of observing

  Temperature data only + large-scale polarization

- Early 2014 — Second data and cosmology results

  Full mission

  Temperature and polarization, first pass

- Mid 2015 — Final data and cosmology results

  Full mission

  Temperature and polarization, second and final pass

Note

- We're still in the early phase of analysis
  - No cosmology results yet
  - No polarization results yet even for "just" astrophysics
- Polarization is harder than temperature
  - With one exception cosmological polarization won't be released until 2014
  - There's a lot I can't talk about! But see A&A vol. 536

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    Planck early results. VI. The High Frequency Instrument data processing
- Lots of hard work but no showstoppers for Planck. But the demands of a full-up space B-mode experiment are much greater.

Planck Firsts

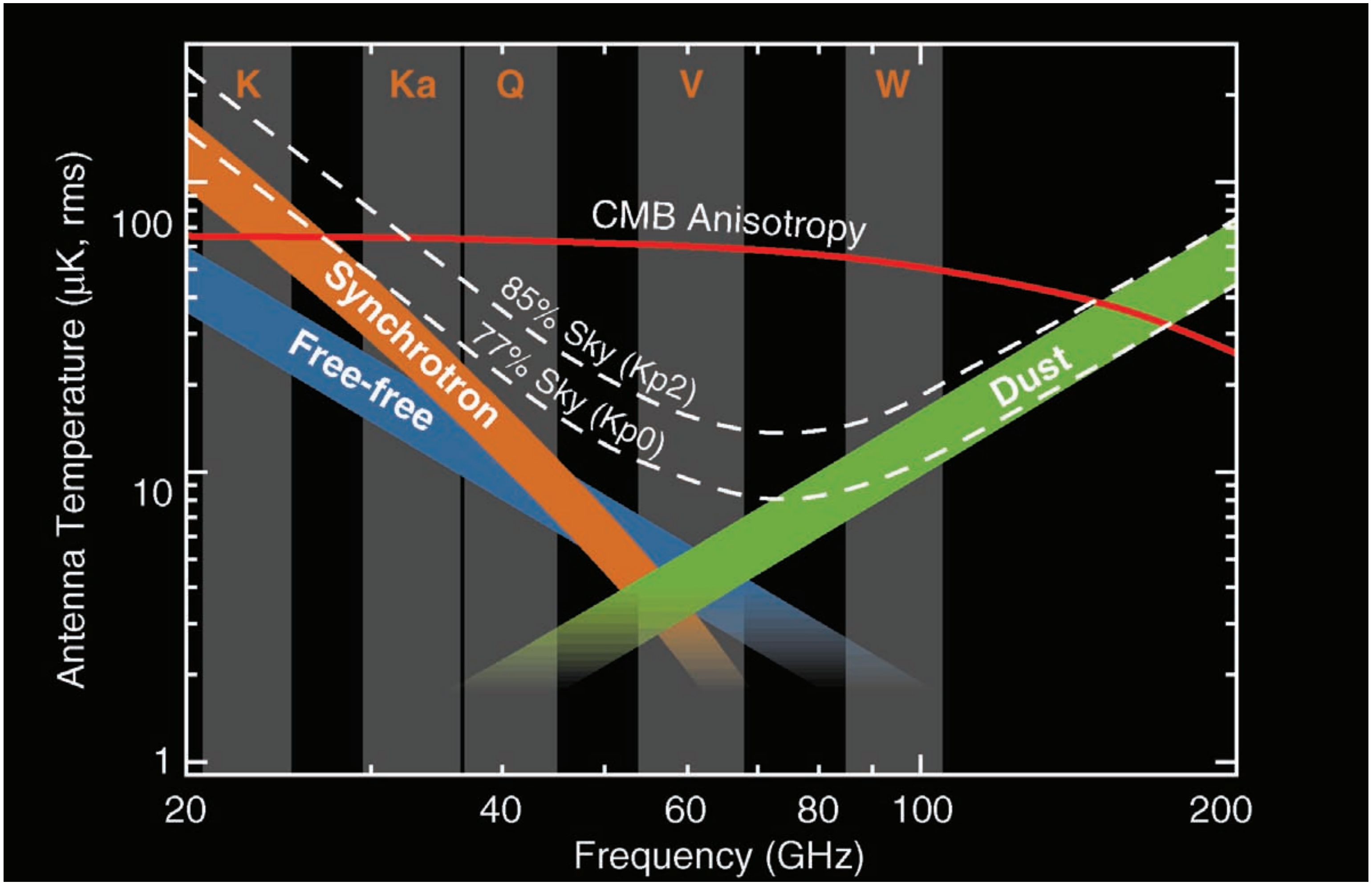
- Tests of key technologies in space:
  - Cryogenic bolometers at 0.1 K
  - Cryogenic amplifiers at 20 K
  - Thermal system that provides 20 K and 0.1 K with no stored cryogens
- First maps of the sky from 143 to 857 GHz sensitive to discrete sources
- Sensitive measurement of polarized foregrounds from 30 to 353 GHz
- Lessons from Planck are applicable to a broad range of cryogenic, long-wavelength mission possibilities, I'll emphasize B-mode polarization, as that is the main concern of the IPSAG.

Lesson #1

B-MODE MEASUREMENTS WILL BE LIMITED BY FOREGROUNDS AND SYSTEMATICS.

- Emphasis on "white-noise" sensitivity, "mapping speed", etc., misses the point.

Foregrounds

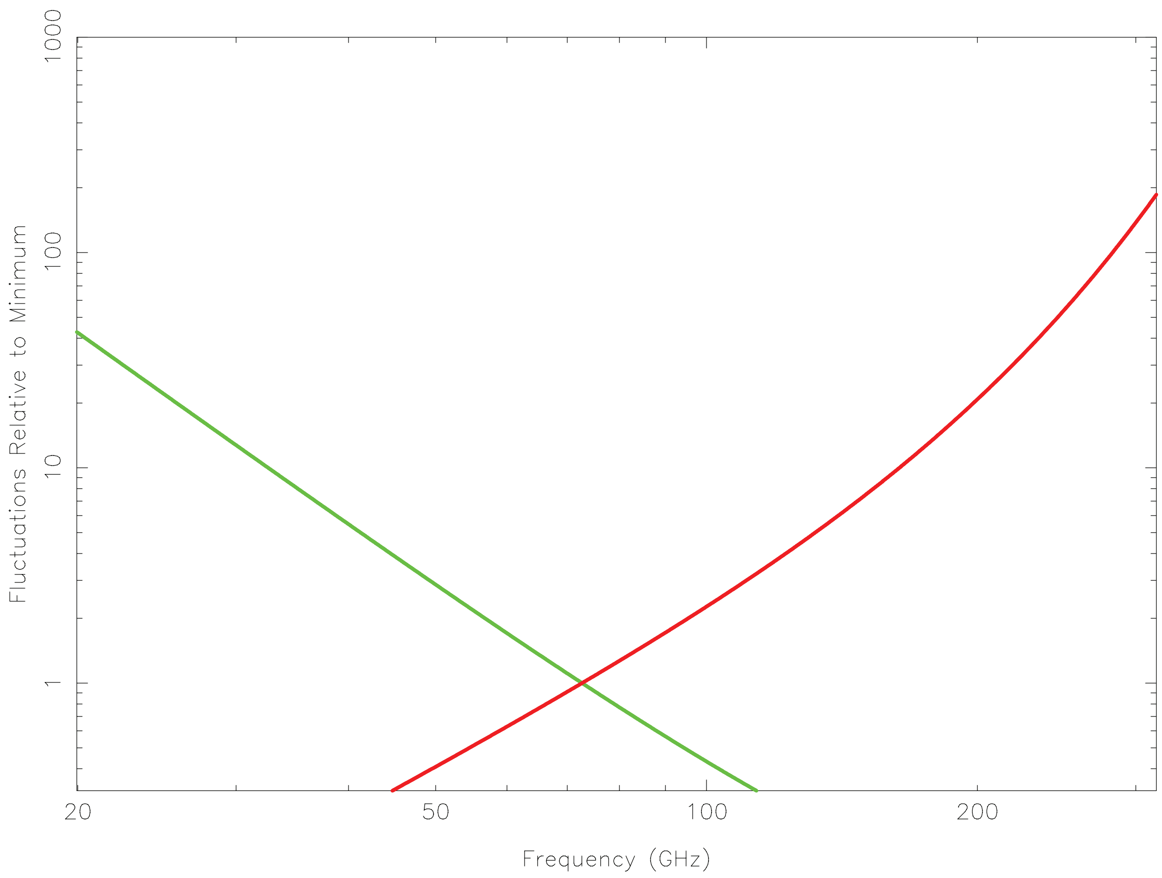


- This is temperature, of course. Life is easy. Sort of. But. . .

N.B.—"Dust" is a frequency-dependent mixture of Galactic dust and the CIB.

Foregrounds—cont'd

- Look at level of synchrotron and dust fluctuations relative to their values at the foreground minimum:



- These are seriously steep functions of frequency!

Foregrounds—cont'd

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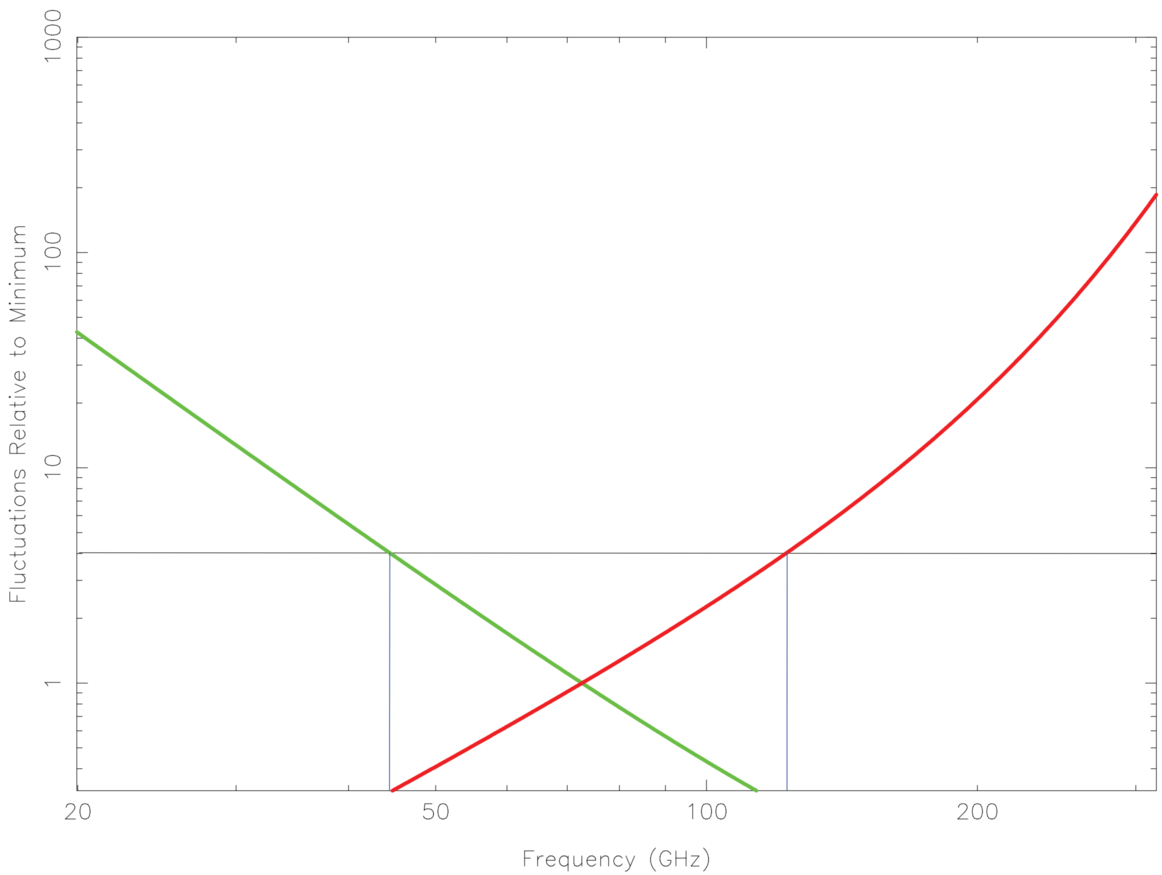

- These are seriously steep functions of frequency!

Foreground Polarization

- From WMAP, e.g., Macellari et al. MNRAS 418, 888, 2011
  - Synchrotron: 5–40%, higher at high latitudes. Average for $|b| > 20°$ is 19.3%
  - Free-free and anomalous dust relatively unpolarized
- From Archeops, e.g., Ponthieu et al. A&A 444, 327, 2005
  - Dust: 5–10%, even higher
  - "We have extrapolated our results to the reference frequency 100 GHz. . .The upper limit on the E and B modes becomes 0.2 $\mu K^2_{\rm CMB}$. These values show that even at 100 GHz where dust radiation is expected to be lower than the CMB, its polarization may be very significant compared to the CMB and should be subtracted with care from the observations."
- Whereas for the CMB, polarization fractions are low (E) and really low (B).

There is no escape from foregrounds in polarization!!!

What About...?

- "Observe above (below) the minimum. Better to observe one foreground well than many."
- "Dust isn't highly polarized."
- "Observe in really clean patches of sky."

Foregrounds—cont'd

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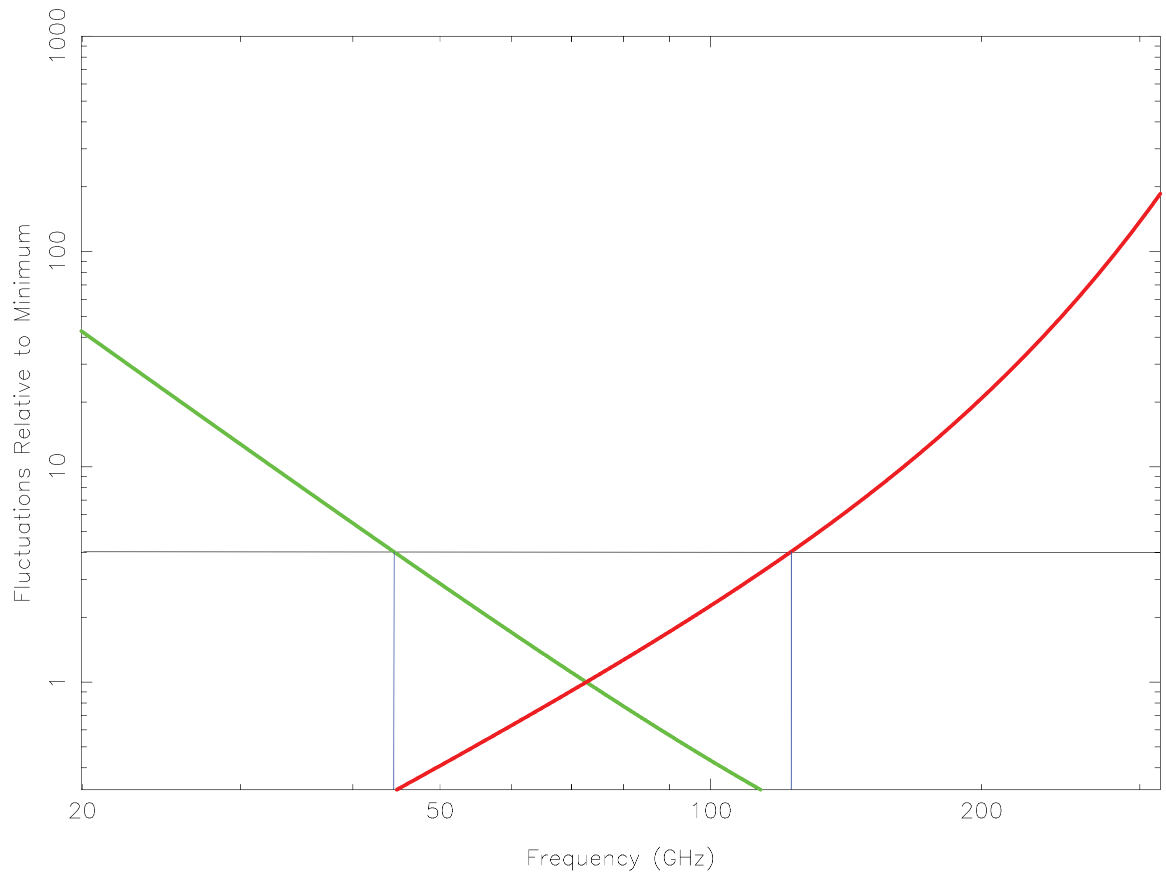


- That leaves half the foregrounds at the minimum unconstrained.

Foregrounds—cont'd

- "Dust isn't highly polarized."

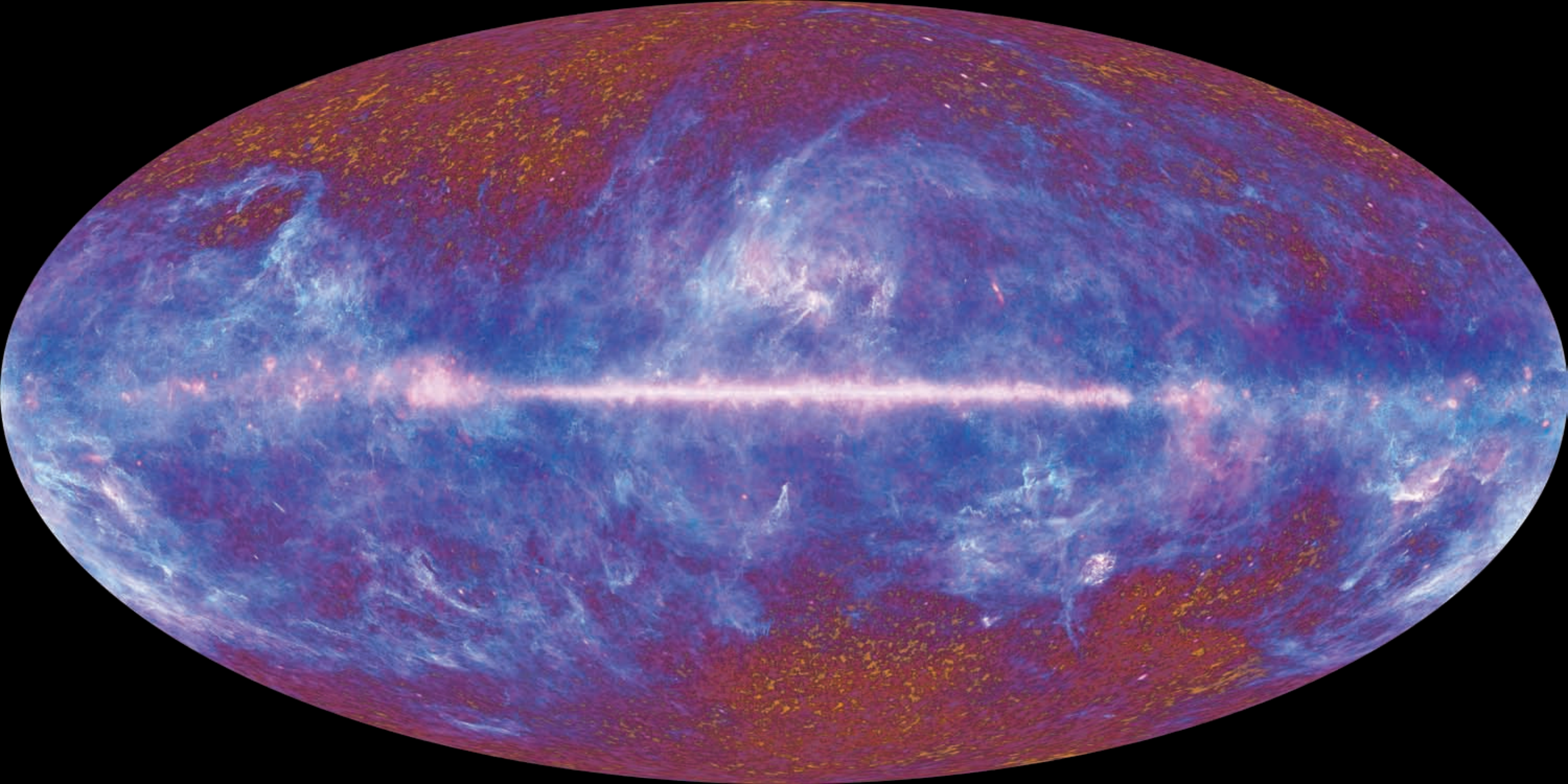
$$\boxed{\textsc{Archeops!}}$$

Foregrounds—cont'd

- "Observe in really clean patches of sky."

UH, SEE PLANCK IMAGE.

- A space B-mode polarization mission must measure the reionization scales, and that requires a lot of sky. "Clean patches" aren't big enough to do the job.



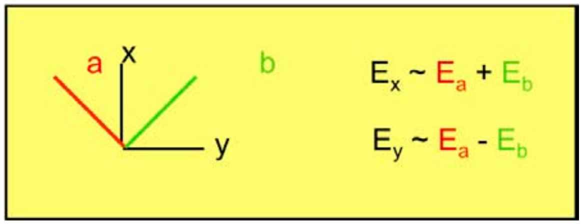
Foregrounds — cont'd

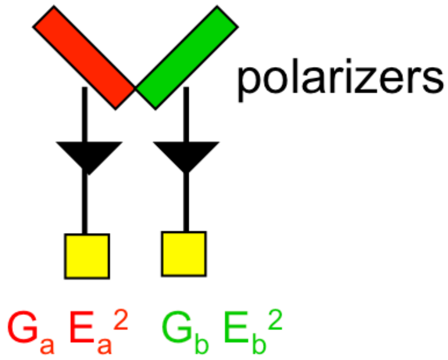
Systematics

- Absolute vs. differential polarimetry
- Cosmic rays (HFI only). Brendan will talk about this.
- Time response (related to beams)
- Beams, main and sidelobes (related to time response)
- Bandpasses (related to foregrounds)

Systematics: ΔP, ΔT

- Planck was optimized to measure temperature anisotropies.
- Both HFI and LFI measure E_x and E_y separately behind linear polarizers, then combine the two to get $Q = E_x^2 - E_y^2$ and $U = E_x E_y$, or whatever.

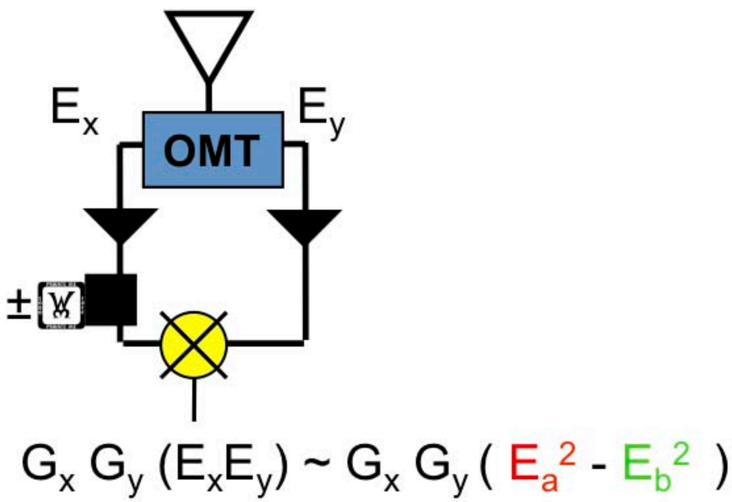




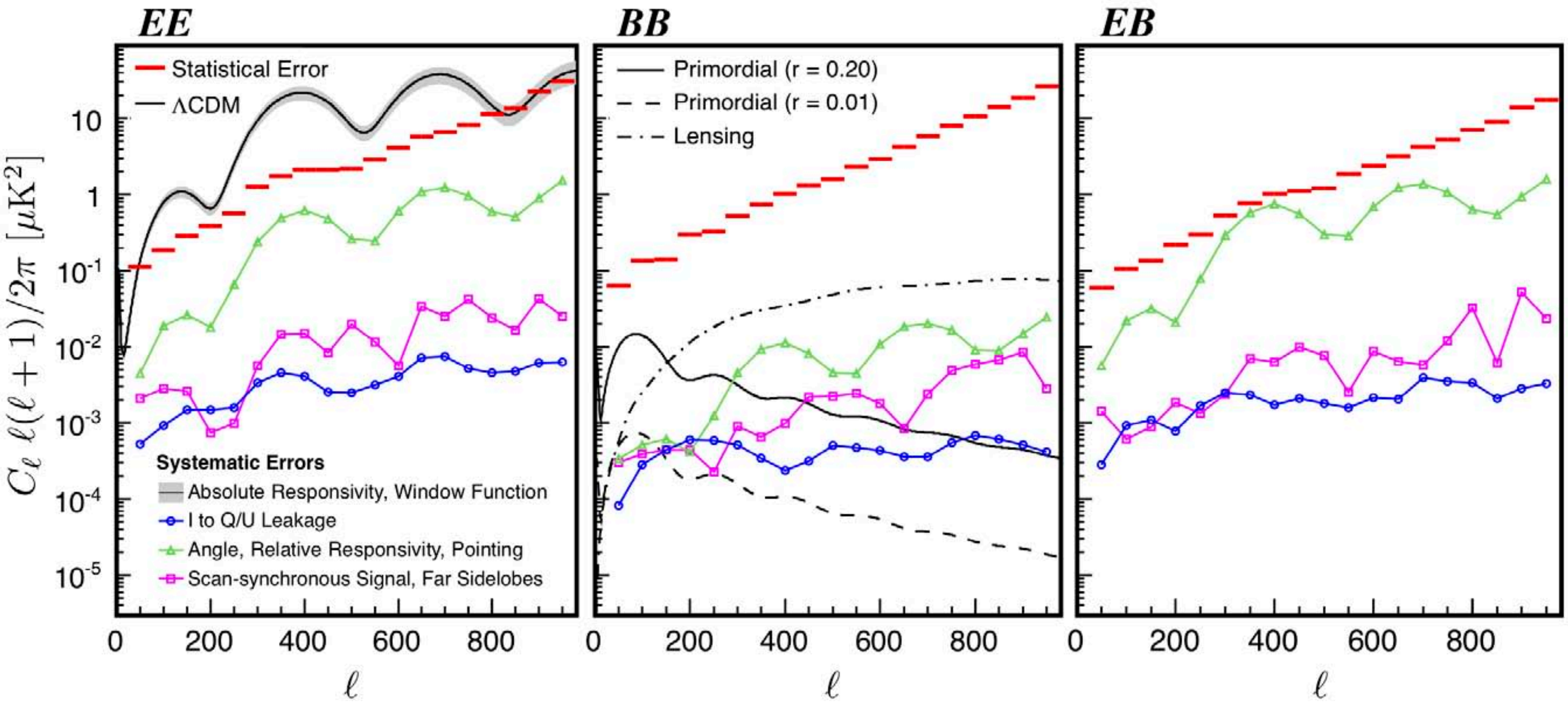
- Systematic errors are produced by
  - Cross-polarization
  - "Gain" mismatches between the two detectors differenced
  - Long time constants that are not pure exponentials, exacerbated by cosmic rays (HFI)
  - Pointing mismatches between the two detectors differenced

Systematics: ΔP — cont'd

- Correlation polarimeters work really well, and reduce the systematics on the previous page



For Example



QUIET Collaboration arXiv:1207.5034v1 20 Jul 2012

Fig. 3.— Summary of systematic error assessment for EE (left), BB (middle), and EB (right). The red bars indicate the statistical uncertainties in each bin. Blue, green, and purple points correspond to three categories of systematic errors: I-to-Q/U leakage; polarization angles (absolute and relative), relative responsivities and pointing error; and the residual scan-synchronous signals and far sidelobes. The gray band along the ΛCDM curve in EE corresponds to the uncertainties of multiplicative factors: absolute responsivity and the window function. For BB, all systematic errors are below the level of $r \sim 0.01$ at $\ell \sim 100$. For EE the dominant systematic error is uncertainty in the absolute responsivity, which is a purely multiplicative effect. For EB, the dominant systematic is caused by uncertainties in the polarization detector angle.

Clocks

All time should be referenced to a single clock.

- Time drifts between unsynchronized clocks cause a lot more trouble than any possible benefit gained!

ADCs

> **Know their non-linearities, and take them into account in designing the electronics**

- You'll regret it if you don't!

Beams and Time Response

SIMPLER IS EASIER

Don't compromise required precision and accuracy in ground testing. Bandpasses, for example, are hard to measure in space.

Computing

$\boxed{\text{A LOT IS NEEDED!}}$

- See Julian Borrill's talk in the DE session this afternoon

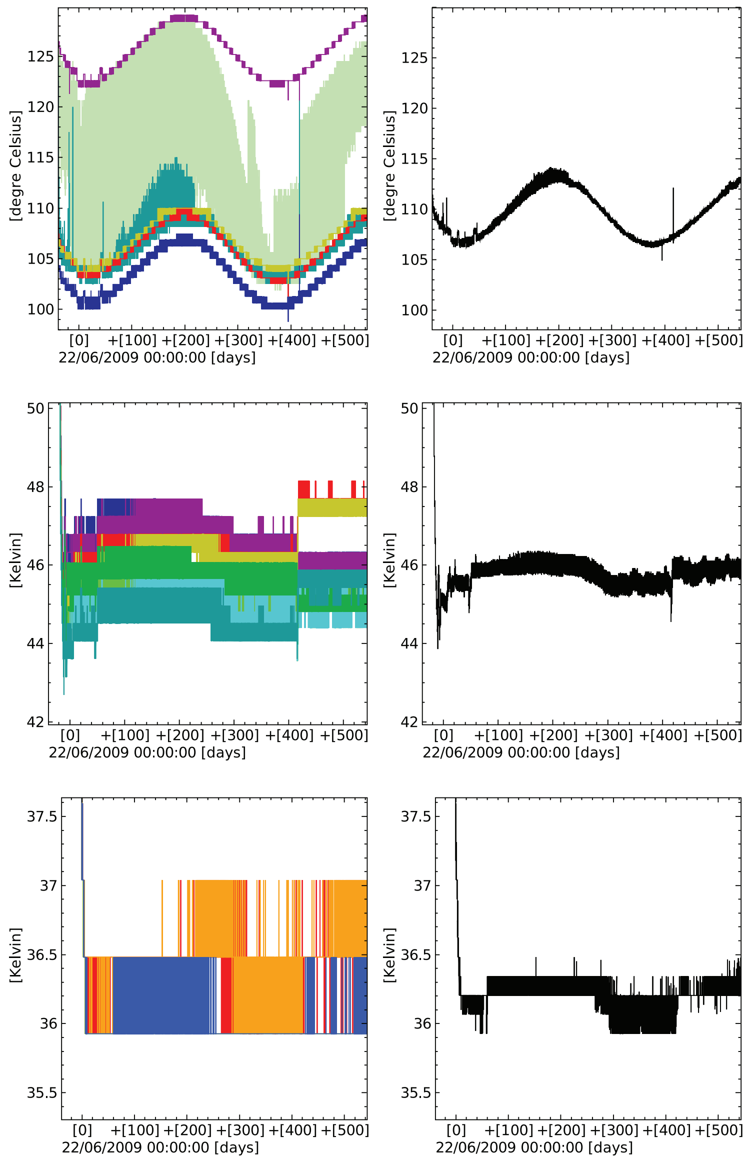
Thermal System Lessons

From Planck early results. II. The thermal performance of Planck

Thermal fluctuations are present in the various temperature stages, particularly near 20 K, but these have not compromised the systematic error budget of the instruments.

- In missions with stringent temperature stability requirements, temperature sensors should be significantly better than on Planck (typically 0.1 K resolution).

Thermal System — cont’d



Solar panel

V-groove 3

Primary mirror

Figure 35. Planck early results. II. The thermal performance of Planck

Seasonal variation in the temperature of the solar panel , V-groove 3, and the primary mirror. Individual readings are shown for multiple temperature sensors on each part of the structure (*left, all three panels*). Quantization effects are clearly visible for V-groove 3 and the primary mirror. These are reduced but not eliminated by averaging the relevant sensors (*black line in all three panels*).

Thermal System — cont'd

- Temperature stability requirements for all spacecraft components and panels should be specified for their effect on the thermal stability of the cryogenic system.
- Excess cooling capacity provides margin in the operation of the cryo chain, but can lead to decreased stability by unstable evaporation of excess cryogenic fluids (helium or hydrogen). Enough adjusment of cooling and PID power is needed to cope with the configuration where all coolers are at their best performance.
- The system definition should carefully consider not only the margins for the planned operating point, but also margins along the entire cooldown path. Coolers have little power when they are far from their optimal operating temperature, and the system could be stuck at a temperature well above the one at which it can operate. The Planck ^{4}He-JT cooler, for example, had its minimum margin when starting to cool down from 20 K, when the heat switch to lower stages was turned on.
- Sub-kelvin stages have been found on Planck to be, as expected, very sensitive to heat input by microvibration from mechanical compressors (there is no other source of microvibrations on Planck).

Thermal System — cont'd

- An end-to-end thermal model is necessary, but that does not imply making a single unified model containing the full complexity of all stages. Such a model would be very complicated. Detailed models of subsystems with empirical interface models to be used in a global model was the philosophy used in Planck, and it worked well.

The Future

- Planck is still at the beginning of its work on polarization
  - No results released yet
  - Much of the analysis yet to come
- Essential information on polarized foregrounds and CMB still to come
- Stay tuned. . .